# On the Importance of Local Sources of Radiation in Cosmological Absorption Systems

Jordi Miralda-Escudé

*The Ohio State University*

jordi@astronomy.ohio-state.edu

## ABSTRACT

An upper limit to the importance of local sources of radiation compared to the cosmic background in cosmological absorption systems is derived, as a simple consequence of the conservation of surface brightness. The limit depends only on the rate of incidence of the absorbers and the mean free path of the radiation. It is found that, on average, the ionizing radiation intensity from local sources in Lyman limit systems at $z > 2$ must be less than half of the intensity of the cosmic background. In absorbers with column densities much lower than Lyman limit systems, the local source contribution must be negligible. The limit on the ratio of local source to background intensities is then applied to the class of damped Ly$\alpha$ absorption systems with detectable excited C II lines. A cooling rate of the gas in these systems has been measured by Wolfe et al. , who assumed that the balancing heating source is photoelectric heating on dust by light at $\sim$ 1500 Å . The intensity from local star formation at this wavelength in this class of damped Ly$\alpha$ systems is found to be at most $\sim 3$ times the background intensity. If the heating source is indeed photoelectric heating of dust, the background created by sources associated with damped Ly$\alpha$ systems can then be estimated from the average cooling rates measured in the absorbers. Current results yield a background intensity higher than previous estimates based on observed galaxy and quasar luminosity functions, although with a large uncertainty. The possibility of other sources of heating, such as shock-heating in a turbulent medium, should be explored.

*Subject headings:* cosmology: theory – diffuse radiation – intergalactic medium – quasars: absorption lines

## 1. Introduction

In the study of the ionization of intergalactic absorption systems observed in the spectra of quasars or other bright optical sources, the question has often been raised of whether the ionizing radiation that illuminates the absorbing gas is dominated by the cosmic background, or by a local source associated with the absorber (usually a galaxy in a dark matter halo). This paper presents a straightforward argument that yields an upper limit to the importance of any local source, demonstrating that local sources can be at most of comparable importance to the cosmic background in typical damped Ly$\alpha$ and Lyman limit systems, and must be negligible compared to the background in any class of absorption systems that have a rate of incidence much higher than that of Lyman limit systems. This upper limit is derived in §2, and an application to the origin of the heating source in damped Ly$\alpha$ systems with detected excited C II where the gas cooling rate can be derived is discussed in §3.

## 2. The maximum average contribution of local sources

Consider the set of absorption systems with an observed column density $N > N_{min}$ of some absorbing atom, with an average rate of incidence per unit redshift on random lines of sight $r(z)$, as a function of redshift $z$. Assume that each such absorber is associated with a halo containing a local source of radiation. In an absorber at impact parameter $b$ from a source of luminosity $L$, the absorbing gas is at a distance larger than $b$ from the source, so the average flux $F_l$ contributed by the local source on the absorbing atoms must be $F_l < L/(4\pi b^2)$. The average surface brightness $s_l$ contributed by the local source over the entire sky is simply $s_l = F_l/(4\pi)$. We define $\bar{F}_l$ and $\bar{s}_l$ as the average values of the local flux and surface brightness over all the absorption systems, which will generally have a range of associated source luminosities and impact parameters.

Any absorber will be illuminated as well by all other sources contributing to the cosmic background. A source that is associated with another absorber at distance $x$ from the first one produces an average flux

$$\bar{F} = \bar{F}_l \frac{b^2}{x^2}\, e^{-x/\lambda(z_a)} \ , \tag{1}$$

where $\lambda(z_a)$ is the mean free path of photons at redshift $z_a$, and we assume for simplicity that $x$ is small compared to the cosmic horizon at $z_a$. We can now imagine this flux spread over the solid angle $\Omega$ over which the absorber is observed with column density above $N_{min}$. For a spherical absorber with column density $N_{min}$ at impact parameter $b$, we have $\Omega = \pi(b^2/x^2)$

(for $x \gg b$), so the mean surface brightness within $\Omega$ is

$$\bar{s} = \frac{\bar{F}}{\Omega} = \frac{\bar{F}_l}{\pi}\, e^{-x/\lambda(z_a)} \ . \tag{2}$$

Hence, the surface brightness of the cosmic background contributed by all the sources associated with the absorbers of rate of incidence $r(z)$ is

$$s_b = \int_{z_a}^{\infty} dz\, r(z) \frac{\bar{F}_l}{\pi}\, e^{-(z-z_a)/\zeta(z_a)} \ , \tag{3}$$

where $\zeta(z_a) = H(z_a)\,(1+z_a)\,\lambda(z_a)/c$ is the redshift interval corresponding to the mean free path $\lambda(z_a)$, and $H(z_a)$ is the Hubble constant at $z_a$. The ratio of the background surface brightness to the average local surface brightness is then

$$\frac{s_b}{\bar{s}_l} = 4 \int_{z_a}^{\infty} dz\, r(z)\, e^{-(z-z_a)/\zeta(z_a)} \ . \tag{4}$$

We note that $s_b$ is the intensity of the *fraction* of the background radiation that is contributed by sources associated with the set of absorbers being considered. In practice, most of the background radiation may be contributed by other sources and may then have an intensity much larger than $s_b$. For example, the background may be produced predominantly by highly luminous quasars and galaxies, whereas most hydrogen absorbers may arise in low-mass halos containing galaxies of low luminosity.

Equation (4) is of course easily generalized to include cosmological effects that become important when the universe is not highly opaque:

$$\frac{s_b(\nu)}{\bar{s}_l(\nu)} = 4 \int_{z_a}^{\infty} dz\, r(z)\, \frac{\bar{F}_l[\nu(1+z)/(1+z_a), z]}{\bar{F}_l(\nu, z_a)} \left(\frac{1+z_a}{1+z}\right)^3 e^{-\tau(z,z_a)} \ , \tag{5}$$

where $\nu$ is the frequency, $\bar{F}_l(\nu, z)$ is the average local flux per unit frequency at frequency $\nu$ and redshift $z$, and the optical depth from $z$ to $z_a$ is

$$\tau(z, z_a) = \int_{z_a}^{\infty} \frac{dz}{1+z} \frac{c}{H(z)\lambda(z)} \ . \tag{6}$$

We now apply equation (4) to hydrogen Ly$\alpha$ absorption systems, and consider photons near the hydrogen Lyman limit (where the mean free path is shortest). Assuming that the column density distribution of absorbers is $f(N_{HI})\, dN_{HI} = N_{HI}^{-1.5}\, dN_{HI}$ (Petitjean et al. 1993), the mean free path of photons at frequencies just above the Lyman limit is $\lambda = \lambda_{LL}/\sqrt{\pi}$, where $\lambda_{LL}$ is the mean separation between Lyman limit systems with $N_{HI} > 1.6 \times 10^{17}\,\mathrm{cm}^{-2}$ (see eq. [3] in Miralda-Escudé 2003). Hence, for Lyman limit systems themselves, their rate of incidence is $r_{LL}(z) = [\sqrt{\pi}\zeta(z)]^{-1}$, and using eq. (4), we find that the ratio of the background flux to the local source flux is

$$\frac{s_b}{\bar{s}_{l,LL}} > 4 \int_{z_a}^{\infty} \frac{dz}{\sqrt{\pi}\zeta(z)}\, e^{-(z-z_a)/\zeta(z_a)} \simeq 2.3 \ , \tag{7}$$

where we have neglected the variation of $\zeta$ with $z$. This approximation is adequate if the universe is opaque to ionizing photons, an assumption that we have already made by neglecting the cosmological terms from equation [5]). We have used the $>$ sign as a reminder that the background may be contributed mostly by sources that are not associated with typical Lyman limit systems, and could then be much more intense. Uncertainties in the observed column density distribution can make only small changes to the numerical value in equation (7). Therefore, we have shown that *on average, the intensity due to local sources in Lyman limit systems cannot be more than about half the intensity of the cosmic background.*

The above statement is valid at all redshifts when the universe is opaque, or $z \gtrsim 1.5$. At low redshifts, the universe becomes transparent and Lyman limit systems are found only in a small fraction of lines of sight, so local sources may then be more important.

For lower column density systems, the importance of local sources must be even smaller in proportion to the inverse of the rate of incidence, according to eq. (4). For example, for systems with $N_{HI} > 10^{15}\,\mathrm{cm}{-2}$, and assuming as before that $r(z) \propto N_{HI}^{-0.5}$, the flux from a local source can contribute at most 4% of the background flux.

In a recent paper, Schaye (2004) claimed that local sources could, under some assumptions, be dominant or comparable to the background in absorption systems with $N_{HI} > 10^{15} f^{-2}$ to $10^{16} f^{-2}\,\mathrm{cm}^{-2}$, depending on the model used for the column density distribution (see his Table 1), where $f$ is a parameter depending on the escape fraction of ionizing photons from Lyman break galaxies (the dependence proportional to $f^{-2}$ is valid only for $r(z) \propto N_{HI}^{-0.5}$). Schaye (2004) concluded that, for $f$ not much smaller than unity, this may compromise the validity of ionization models for the metal lines in these absorbers (e.g., Steidel & Sargent 1992; Boksenberg et al. 2003). We have shown here that, in any class absorbers with a rate of incidence that is not substantially smaller than that of Lyman limit systems at $z \gtrsim 1.5$, local sources cannot possibly dominate above the background. Schaye (2004) computed the flux from local sources using models and assumptions for the observed luminosity functions of galaxies and escape fractions, and he estimated the background intensity separately from measurements of the Ly$\alpha$ forest transmitted flux. In Schaye's models in which radiation from local sources can be of greater importance compared to the background than the result we obtain here, the galaxies he postulated as local sources would produce a background of higher intensity than he assumed.

The argument presented here is not modified if the absorbers consist of clusters of clouds, because the radiation from a local source that is either in the same cloud or the same cluster of clouds as the absorbing gas is subject to the same limit of equation (4).

## 3. Implications for the local ultraviolet flux in damped Ly$\alpha$ systems

The radiation flux present in absorption systems is also important for the heating rate of dense, metal-enriched gas in damped Ly$\alpha$ systems. The photoelectric effect on dust grains produced by ambient ultraviolet photons may be the primary heating source of some of this gas, and is believed to be the main heating source for the diffuse interstellar medium in the Milky Way disk (e.g., Watson 1972; Weingartner & Draine 2001). Wolfe et al. (2003a) determined the cooling rate through the 158 $\mu$m emission by C II in a set of damped Ly$\alpha$ systems, by measuring the column density of the excited C II (or C II$^*$ ) state. They then derived the intensity of ultraviolet radiation that would be required to balance this cooling from the photoelectric heating effect on dust grains (Wolfe et al. 2003b, 2004).

Photoelectric heating is caused by radiation of wavelengths $\lesssim 2000$ Å. In practice, only photons with wavelengths longer than 912 Å are important, because the cosmic background intensity decreases by a large factor at shorter wavelengths (due to the Lyman break feature of star-forming galaxies), and because any photons at shorter wavelengths would be absorbed by hydrogen before reaching the interior of a damped Ly$\alpha$ system. The maximum redshift range over which the average photon at wavelength $\sim 1500$ Å has propagated is $\Delta z/(1+z) = (1 - 912/1500)$. Taking the mean free path $\zeta_{UV}(z)$ of these photons to be half the maximum distance travelled before they lose the ability to produce the photoelectric effect due to redshift, we obtain $\zeta(z)/(1+z) \sim 0.2$. With a rate of incidence for damped systems of $r(z) \simeq 0.25[(1+z)/4]$ (Storrie-Lombardi & Wolfe 2000), we find from eq. (4):

$$\frac{s_b}{\bar{s}_{l,d}} > 4 \int_{z_a}^{\infty} dz\, r(z)\, e^{-(z-z_a)/\zeta(z_a)} \simeq 4r(z_a)\zeta(z_a) \simeq 0.8 \left(\frac{1+z}{4}\right)^2 . \qquad (8)$$

Hence, we see that the ultraviolet radiation from the cosmic background cannot be much less than the radiation from local star formation.

Wolfe et al. (2004) detected absorption by C II$^*$ for about half of the damped Ly$\alpha$ systems in a randomly selected sample. They found that if the cooling rate inferred for these systems is balanced by photoelectric heating on dust grains, then the mean ambient radiation intensity at 1500 Å in this class of damped Ly$\alpha$ absorbers is in the range $10^{-19}$ to $10^{-18}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$. According to our formula (8), if this radiation is present in all damped systems, then the background radiation should be fainter than the average local source by only a factor $\sim 0.8$ at $z = 3$. If the damped systems without detected C II$^*$ are a different class of absorbers with much weaker local sources of radiation, then the rate of incidence of the damped systems with detected C II$^*$ is reduced by a half, so equation (8) shows the background must have an intensity of at least 0.4 times the average local source intensity, at the lowest. If we take a value of $3 \times 10^{-19}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$ for the average ambient intensity, we find that the background intensity that is contributed by the same sources associated with this population of damped Ly$\alpha$ systems would have to be at least $10^{-19}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$. This is already higher than the background estimated by the Haardt & Madau (1996) model based on the observed galaxy population at high redshift, which is $3 \times 10^{-20}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$ at 1500 Å(see Fig. 1 in Wolfe et al. 2004).

To make this into a precise estimate of the ultraviolet background at high redshift, the average heating rate in damped Ly$\alpha$ systems required by the C II$^*$ observations needs to be more accurately determined. A possible problem with this method is that other sources of heating may be important in addition to photoelectric heating of dust, for the typical conditions in damped Ly$\alpha$ systems. A likely source of heating may be shock-heating due to cloud collisions. The observed multiple absorption components in the metal lines associated with damped Ly$\alpha$ systems (Prochaska & Wolfe 1997, 1998) indicate a level of turbulence much higher than that in the Milky Way disk, implying that cloud collisions must occur frequently and yielding a minimum heating rate (McDonald & Miralda-Escudé 1999). For example, for the typical velocity separations among the absorption components of $v \sim 50\,\mathrm{km\,s^{-1}}$, and dynamical times $t_d \sim 10^8$ years, the characteristic rate per hydrogen atom would be $m_H v^2/t_d \sim 10^{-26}\,\mathrm{erg\,s^{-1}}$, comparable to the values found by Wolfe et al. (2004). However, the cooling inferred from the C II$^*$ column densities must take place in cold neutral gas, at $T < 1000$ K, and the energy from cloud collisions at the high velocities mentioned above would probably be radiated mostly from gas at higher temperature. It is not clear how much of the turbulent energy could be transferred to cold gas and radiated there. We note also that although Wolfe et al. (2004) mention the observed correlation of their derived heating rate with metallicity as evidence that heating is due to the photoelectric effect on dust, this correlation could be related to other expected correlations of metallicity with halo velocity dispersion and impact parameter (which affect the cloud collision velocities and dynamical time).

## 4. Conclusions

We have presented a general formula that gives an upper limit to the possible contribution of local sources to the total radiation flux illuminating gas in absorption systems, compared to the contribution from the cosmic background radiation. This upper limit demonstrates that absorption systems that are more abundant than Lyman limit systems cannot be affected by radiation dominated by a local source, on average. A useful application of this upper limit is found when it is applied to a class of absorbers that are required to be irradiated by a minimum flux level: the background intensity generated by all the sources associated with these absorbers can then be estimated. In the case of damped Ly$\alpha$ systems with detected C II$^*$ absorption lines, we find that if their gas is in fact heated by photoelectric heating on dust at the level that has been claimed by Wolfe et al. (2004), then the cosmic ultraviolet background is likely dominated by the sources associated with these damped Ly$\alpha$ absorbers and is higher than the previously estimated background from known galaxies and quasars.

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